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PRELIMINARY REPORT UPON THE POSSIBILITY OF CON-  
TROLLING THE LAND SLIDES ADJACENT TO THE  
PANAMA CANAL

By the Committee of the National Academy of Sciences Appointed  
at the Request of the President of the United States

Dated, February 4, 1916. Received, March 16, 1916

INTRODUCTION

The Committee of the National Academy of Sciences, appointed November 18, 1915, at the request of President Woodrow Wilson "to consider and report upon the possibility of controlling the slides which are seriously interfering with the use of the Panama Canal," submits this its preliminary report.

The Committee as originally appointed consisted of thirteen persons. For various reasons four (Messrs. A. L. DAY, G. F. BECKER, C. D. WALCOTT, and R. S. WOODWARD) were unable to visit the canal and participate in the deliberations of the Committee. Those who took part in the preparation of this report are as follows:

|                 |                  |                |
|-----------------|------------------|----------------|
| C. R. VAN HISE, | WHITMAN CROSS,   | J. R. FREEMAN, |
| H. L. ABBOTT,   | R. C. CARPENTER, | J. F. HAYFORD, |
| J. C. BRANNER,  | A. P. DAVIS,     | H. F. REID.    |

These members, who will be spoken of as 'the Committee' in the report, sailed from New Orleans December 11, and arrived at Panama December 19. All spent two weeks in the Canal Zone, and three of them several days longer, working upon the problem submitted to them.

The part of the Canal cut between Bas Obispo and Pedro Miguel will be called the Gaillard Cut in accordance with the official use of that term. The deepest part of the Gaillard Cut, at the continental divide, about one mile in length, will be called the Culebra District.

The hill upon which the village of Culebra stands will be called Culebra Hill.

The general direction of the Canal is nearly northwest and southeast, but nearer north and south than east and west. The various stretches vary considerably in this direction. For the sake of brevity in description, the Canal will be regarded as running north and south, and directions at right angles to the Canal will be called east and west and those parallel with it north and south.

The term 'slides' when unqualified will be applied alike to material which is now in motion and to that which once has been in motion but is now quiescent. Where it is necessary to discriminate between these two conditions of the slides, one will be called 'active' and the other 'quiescent.'

The Culebra district was visited by all members of the Committee five days, and a number of the Committee spent several additional days in this area. The attention of the Committee was primarily directed to the question of the control of the active East and West Culebra Slides, but the extensive Cucaracha Slide, now quiescent, was also examined with care. The Committee also examined the massive hills of the Culebra District and especially Gold, Culebra, Zion and Contractors Hills, all of which are adjacent to the great slides.

The work of the Committee in the field was facilitated in every way by Major General George W. Goethals, Lieut. Col. Chester H. Harding, Lieut. Col. Jay J. Morrow and Rear Admiral H. H. Rousseau; General Goethals furnished records from his office, a brief history of the slides and their movements, and much other information which the Committee desired; in short, all possible help has been given to the Committee so that its members could carry on their work most effectively in their own way.

The Committee has profited greatly by the geological studies of Mr. Donald F. MacDonald and by conferences with him in the field and in the office.

As the uninterrupted operation of the Panama Canal is a matter of great national importance, the Committee plans a further study of the available data and expects in due time to make a fuller report; but it seems desirable to present promptly to President Wilson, a preliminary report containing the views of the Committee (so far as they can now be formulated), and such practical suggestions as the Committee is able to offer.

## THE THREE GREAT SLIDES

The slides which led to the closing of the Canal on September 18, 1915, were the great East Culebra and West Culebra Slides. General Goethals has described these slides in an article prepared for the press, under date November 15, 1915, and from this article the following statements are taken:

The East Culebra Slide began on October 14, 1914, without any warning and a section of the east bank north of Gold Hill settled vertically 20 feet. This section measured 2,000 feet (now extended to 2,700 feet) along the prism face and extended back 1,000 feet from the axis of the Canal, generally along an irregular curved line. The top of the bank was from 300 to 350 feet above sea level, and the extension of the ground eastward was relatively flat country. In the settlement, the upper portion which broke away remained practically parallel to its original position, and the benches which formed the upper part of the slide had not changed their relative positions, though they were badly broken up, while the lower strata were squeezed out across the Canal. Subsequently the broken mass moved into the cut, reducing the depth of the water from 45 feet to 9 inches at one point. Until August, 1915, the dredges were able for the most part to keep up with the movement as it came down, and probably would have been able to maintain this condition had not a movement occurred on the west bank, necessitating work on this side to the detriment of the east side.

A crack was found on the slope of Zion Hill in June, 1914, but observations made upon it showed no movement and the solidity of the hill was never doubted. Subsequent to the break on the east side, a gradual but general breaking up of the west bank followed, and the crack on the slope increased in size and new ones developed farther up the hill, until finally one extended to the elevation of 480, the limit of the present break. The movement into the cut from the west bank occurred early in August, 1915, when a section of Zion Hill broke away and settled down. The edge of the break on this side is also a curve.

The movements from the two sides are towards the central portion of the enclosed area, and at this central portion is the obstruction to the channel. It first appeared as an island forced up from the bottom, then as a peninsula projecting from the east bank, and finally was pushed entirely across the channel completely closing it. . . .

The length of the slides, which are directly opposite each other, is approximately 2,200 feet (the channel through which is navigable with the exception of 600 feet); the banks are 300 to 350 feet above sea level on the east and extend up to 480 feet above sea level on the west. The area of the territory affected on the east side covers 81 acres and on the west 78.5 acres.

Assuming that all material lying above planes extending from the outside limits of the bottom of the prism, reference 40, up to the limits of the

breaks, will move into the cut, 7,000,000 cubic yards will have to be removed before the slides are entirely stopped. Mr. Comber, Resident Engineer of the Dredging Division, assumed a surface parallel to the surface existing on October 14, the date of the last complete survey, and 45 feet below it, on which basis 13,000,000 cubic yards would be the quantity to be handled. He thinks, however, that a mean between the two amounts may be more nearly correct, which was the method of arriving at the 10,000,000 cubic yard figure which has appeared in the press. It is at best only a guess. It must not be inferred from this that the Canal will be closed until this amount is dredged, for such is not the case; on the contrary it is the intention to pass ships as soon as the channel is secured through the remaining 600 feet, and there are reasonable grounds for assuming that a channel through the obstructed area can be maintained.

The active West Culebra Slide extends 2900 feet along the Canal, and 1350 feet at right angles to it measured from the axis of the Canal to the furthest point of the slide.

Of the slides now quiescent, the most important is the Cucaracha. General Goethals writes of it, in the article already mentioned:

On January 20, 1913, a break occurred at Cucaracha by which the rock bluff which was holding back the upper mass of clay broke at or below the bottom level of the Canal, completely filling the prism with clay and rock, reaching to 69 feet above sea level on the opposite or west side of the cut. The length of the prism so filled was 1600 feet. Steam shovels were scarcely able to keep pace with the movement, tracks were covered and disarranged, shovels overturned, and the difficulties of transportation increased, since only tail tracks sufficient for two or three cars could be maintained. Furthermore, the soft material increased the difficulties of the dumps. As the movement continued the clay broke farther and farther up the hillside.

The Cucaracha Slide, as stated, extended 1600 feet along the Canal, and 1880 feet at right angles to it.

*Dominant Importance of the Three Great Slides.*—According to Mr. W. G. Comber, Resident Engineer in charge of Dredging, the acreage of the three great slides is as follows:

|                         |       |
|-------------------------|-------|
| West Culebra Slide..... | 60.8  |
| East Culebra Slide..... | 70.5  |
| Cucaracha Slide.....    | 60.4  |
| Total.....              | 201.7 |

In contrast with this, the total area of all other slides is 112 acres.

The dominance of the three great slides appears even more marked when the amounts of excavated and moving material are considered.

Mr. Comber's figures for excavation accomplished to December 30, 1915, are:

|                         | <i>cu. yds.</i> |
|-------------------------|-----------------|
| West Culebra Slide..... | 10,931,862      |
| East Culebra Slide..... | 14,687,563      |
| Cucaracha Slide.....    | 9,901,602       |
| <hr/>                   |                 |
| Total.....              | 35,521,027      |

In contrast with this amount, the total excavations for the other slides to the same date have been 4,852,648 cubic yards.

If the amounts of material still to be removed are compared, the dominance of the three great slides is maintained. It is estimated that, on December 30, 1915, there remained to be excavated:

|                         | <i>cu. yds.</i> |
|-------------------------|-----------------|
| West Culebra Slide..... | 3,500,000       |
| East Culebra Slide..... | 5,600,000       |
| Cucaracha Slide.....    | 500,000         |
| <hr/>                   |                 |
| Total.....              | 9,600,000       |

The total amount still to be removed from all other slides is estimated at the insignificant amount of 330,000 cubic yards. It thus appears that the amount of material already excavated and still to be removed from the three great slides is estimated at 45,121,027 cubic yards; whereas, the corresponding amount for all the other slides is 5,182,648 cubic yards, or about one-ninth as much.

The foregoing facts are conclusive as to the dominant importance of East Culebra, West Culebra and Cucaracha Slides.

Since the three great slides are all in the Culebra District, this is the chief area of danger. This is the natural consequence of the fact that by far the deepest part of the Canal cut is in this District; and that the weakest of the geological formations, the Cucaracha, is strongly developed here.

Slides may occur in other parts of the Canal, but they will be relatively small, and infrequent; for the banks are not high, and the unstable ground has already slid down so that its surface has approached the angle of repose. Should slides occur, they are not likely to menace the operation of the Canal. Slides, great enough seriously to obstruct traffic in the Canal, could occur only in the Culebra District, which is but one mile long. The possibility of great slides in this section has therefore claimed the most careful consideration of the Committee.

*General Features of the Culebra District.*—In order that the views of the Committee may be clearly conveyed, it is necessary briefly to mention and to illustrate by a map and photographs, the more important features of the Culebra District.

The Canal here traverses the highest land in its course. On the east side, rising abruptly from the Canal, is Gold Hill. This is the highest hill near the Canal; it reaches a height of 660 feet above sea level, or 620 feet above the bottom of the Canal. It is composed mainly of hard intrusive basalt and hard tuff nearly surrounded by basalt. It separates the Cucaracha slide on the south from the East Culebra slide on the north. These slides have caused great breaks in the north and south flanks of Gold Hill, leaving nearly vertical cliffs, which are 275 feet high on the south flank. On the opposite western side of the Canal there are three prominent hills, Culebra, Zion, and Contractors Hills, in order from south to north. Their elevations are:

|                       | <i>Above Sea<br/>Level</i> | <i>Above bottom<br/>of Canal</i> |
|-----------------------|----------------------------|----------------------------------|
| Contractors Hill..... | 415                        | 375                              |
| Zion Hill.....        | 570                        | 530                              |
| Culebra Hill.....     | 390                        | 350                              |

Zion Hill is of intrusive basalt, the other two mainly of hard tuff with some basalt. Contractors Hill nearly touches the waters of the Canal opposite Cucaracha Slide. Zion and Culebra Hills stand about 1500 and 1200 feet, respectively, from the Canal, and in front of them lies the West Culebra Slide. The slide has caused breaks in both of these hills. In the eastern front of Culebra Hill a road was carried down and a number of houses had to be removed; cracks roughly parallel to the Canal have formed for a distance of about 100 feet beyond the prominent break which seems to be the western limit of the slide at the present time, and extend to within 250 feet of the summit of the hill. Zion Hill also has suffered; a large mass has fallen from its eastern face leaving a vertical cliff, whose edge is only about 50 feet from the top of the hill. Contractors Hill has not been affected by the slides.

The great slides occur in the low ground adjacent to these hills where a large amount of softer rocks had already been removed by natural erosion before the excavation of the Canal was begun.

*Relations of the Great Slides to the Hills.*—The Cucaracha Slide is mainly confined to the area between Gold Hill and a subordinate basalt mass to the south. It extends from the Canal for a considerable distance east of the crest of Gold Hill; and its head reaches the subordinate

divide to the east. It is estimated that the Cucaracha Slide drains an area of 80 acres. The slide is sharply limited on the north by the break in Gold Hill already mentioned, which extends approximately at right angles to the Canal; its southern limit is not so well defined.

The limit of the East Culebra Slide is sharply marked on the south by the break through the north part of Gold Hill which runs approximately at right angles to the Canal. The Northern boundary is not so sharply marked. The slide extends slightly beyond the subordinate divide on the east, so that east of the slide the drainage is away from the Canal.

The West Culebra Slide is limited on the south by breaks beginning at the Canal some distance north of Contractors Hill; on the west by breaks which are sharply defined in Zion Hill; and less sharply in Culebra Hill. In the narrow valleys between Culebra and Zion Hills and between Zion and Contractors Hills the break extends beyond the divide, and the drainage is to the west.

*Possible Extensions of the Great Slides.*—The very important question now arises: Will the great slides extend their limits and cause further serious trouble?

In general, the Committee believes that no great extension of these slides is probable, because the soft rock constituting a very large part of the slides is quite limited in extent, except east of the East Culebra Slide, and conditions elsewhere are unfavorable for extensions.

The Cucaracha Slide cannot greatly extend its area on account of the basaltic intrusions which surround it; but its eastern and southern limiting banks are still breaking down, and the movement of the slide may be revived to a small degree. Plugs or branches of intrusive basalt standing as obstructions across the former course of the slide restrain its movement; but the strength of these obstructions cannot be determined from present exposures.

The West Culebra Slide is pretty definitely limited on the west by the hard rocks of Culebra and Zion Hills; but between the active part of the slide and Contractors Hill there is a considerable mass of the Cucaracha formation, which seems never to have taken part in the slides. The effect on this mass of the settling of the adjacent moving material cannot certainly be predicted. Indeed it is not impossible that a considerable part of it may finally be set in motion; but the mass involved will be small in comparison with the active West Culebra Slide.

East of East Culebra Slide the soft formation continues, but the slope is gently away from the Canal. Additions to the slide to the east

are possible, but because of the slope and increased distance from the Canal such possible additions would be in decreasing volume. Gold Hill limits the slide to the south.

#### THE SOLIDITY OF THE HILLS OF CULEBRA DISTRICT

In addition to the danger of the slides, is there danger that the Canal may be blocked by the fall of the hills of Culebra District?

These hills are composed of intrusive bodies of basalt, or of masses of the hard Obispo tuff commonly associated with basalt in this district. So far as can be judged from present exposures, they do not rest on the soft Cucaracha formation, but extend far into the earth, and are self-supporting. Rock may slough off from them, but there is no evidence that they will collapse.

*Culebra and Zion Hills.*—The hard tuff of Culebra Hill practically limits the West Culebra Slide in front of it. Cracks have formed in the tuff and it is probable that some of the rock will break off as the slide settles. Zion Hill is a basaltic intrusion, and much rock has fallen from its face; more may follow. But the total amount that may fall will only make a relatively small addition to the upper part of the West Culebra Slide.

*Gold and Contractors Hills.*—Gold and Contractors Hills rise steeply from the banks of the Canal, for 410 feet and 260 feet above the bottom of the Canal, respectively; and then slope more gently to their summits. They are nearly, but not exactly, opposite each other. Gold Hill is chiefly composed of basalt, which formerly spread out near its top, and was partially supported on the softer Cucaracha formation. When the East Culebra and Cucaracha slides became active the support was removed, and a large mass of the basalt fell from the northern and southern sides of the hill. The lower part of Gold Hill on the side towards the Canal is made up of hard Obispo tuff, bounded by a basalt dike, and there is little danger that it will yield.

Contractors Hill is of hard Obispo tuff, which is separated from the Cucaracha by a fault which dips into the hill at an angle of 60 or 70 degrees with the horizontal. There is a possibility that this part of the hill depends more for its support on the Cucaracha beds than seems probable, and as a measure of precaution all reasonable means should be taken to keep the Cucaracha beds in place; and, especially, the fault fissure should be kept closed to prevent water seeping in. If the borings, suggested later, to reveal the underground structure, show that these precautions are unnecessary they can be discontinued.

The excavation of the Canal, and borings in its bottom show that a narrow belt between the two hills is composed of the soft Cucaracha beds; yet to the present time there has been no upheaval of the bottom of this part of the Canal, nor any other sign to indicate that the hills have settled. It is believed, therefore, that the great masses of Gold and Contractors Hills are self-supporting and will remain so. There is no occasion to raze them.

#### CAUSES OF THE SLIDES

On account of their magnitude, the land slides have received serious consideration since the early days of the Canal. But before measures for their control are taken up it is necessary briefly to discuss their causes.

The slides in the Canal Zone are essentially like many in other parts of the world; they are due to the inability of the earth or rock to support the weight of overlying material. Slow processes of natural erosion, rapid cutting by flooded streams and excavations by man frequently lead to landslides. Much of the Canal is cut through weak rocks; and in the Culebra District the prism is exceptionally deep. It is clear that the conditions there are very favorable for slides.

The weakness of the rocks is due to several causes:

*Character of the Rocks of the Culebra District.*—The rocks of Culebra District are of two kinds—stratified and massive. The chief material involved in the slides is the stratified Cucaracha formation. It is greenish grey in color, largely composed of clayey material with some layers of rather finely banded volcanic sandstone or tuff, only weakly consolidated. The Cucaracha beds are limited, along the line of the Canal, to the Culebra District but they have a thickness in places of over 400 feet. The soft slippery nature of its materials and their loose, unconsolidated condition, make it unusually weak and unable to sustain any considerable load.

The Cucaracha beds alone are responsible for the great slides. The Obispo tuff is a rather coarsely fragmental rock, roughly stratified; masses of the tuff and of the massive columnar basalt have broken from the hills and added some material to the slides, but they have had no part in starting them.

*Structural Weakness.*—The rocks, both stratified and massive, as shown by the work of Mr. MacDonald, are cut by numerous faults and this is true of the rocks throughout the Gaillard Cut. Where there is a fault, the rocks have previously been broken; and therefore, present a place

of exceptional weakness. Some of the smaller slides outside the Culebra District are limited by faults.

An important source of weakness is the fracturing of the rocks by complex sets of joints. They occur in both stratified and massive rocks. The friable parts of the Cucaracha formation are broken by joints into fragments of various sizes down to a fraction of an inch. The massive rocks are fractured in every direction by joints on a much larger scale.

*Earthquakes.*—A consideration of the earthquakes felt in the Canal Zone and a careful examination of the instrumental records kept near the Pacific end of the Canal since the end of 1908 dispel fear of serious damage to the Canal or its accessories by earthquakes. A number of pretty sharp shocks have been felt in the Zone but they have originated at a distance of about 120 miles from the Zone. A few fairly sharp shocks had their origin about 80 miles distant; and two or three, which were not felt, and which made a very feeble record on the delicate seismographs, were much nearer. At the time of the very sharp shocks of October, 1913, a prism of earth 60 feet high and with a base of about 100 square feet broke off the steep slope near the top of the Cucaracha Slide; this is quite insignificant. There is no evidence that any of the slides have been started or increased by earthquakes.

*The Heavy Rainfall.*—Investigations in many parts of the world have shown that excessive water in the ground is a great promoter of landslides. The strength of the Cucaracha clays is greatly decreased by the presence of water, and the heavy tropical rains keep them nearly saturated the greater part of the year; for the broken and irregular surface of the slides and the open cracks around their borders greedily drink in the water that falls upon them.

In the Culebra District the average rainfall since 1884 has been 87.68 inches per annum, and during the time of the excavation of the Canal it has been 84.75 inches per annum. Moreover this rainfall is almost wholly concentrated in eight months of the year. The average for the rainy months during the period of excavation of the Canal by the United States, from the middle of April to the middle of December has been 80.01 inches. Where nearly seven feet of water fall upon the surface of the country within eight months of the year, it is not surprising that there is difficulty in controlling the underground seepage. Indeed during these months the ground water table is practically at the surface, except possibly on the steeper slopes; and the movement of the underground water is so slow that even in the dry season the water table is not far from the surface in the level country. The New French Company found that the water table at the two points of the East Culebra

Slide was six and sixteen feet below the surface respectively. On the summit of Gold Hill, the ground water falls 40 feet below the surface in the dry season, as indicated by the zone of weathering.

#### REMEDIAL MEASURES

All slide material which reaches the Canal must, of course, be removed at a certain expense and inconvenience. This work is being prosecuted by the engineers with great vigor. They estimate that about 9,000,000 cubic yards will have to be removed between the two Culebra Slides; and the dredges can remove 1,000,000 cubic yards a month. But it must not be supposed that the Canal will remain closed for nine months; as soon as the channel has been sufficiently deepened and the movement of the slides becomes so slow that the dredges, even when interrupted by the passage of ships, can more than keep pace with them the Canal may be opened for navigation. This time is probably not far off.

The Committee believes that some sliding ground will continue to enter the Canal for several years to come, though in diminishing amounts. Any relatively inexpensive measures which tend to arrest the present active slides, or which promise to reduce the charge against maintenance of the Canal in the future are fully warranted.

The composition of the rocks, their structural weakness, and earthquakes are beyond the control of man, but a partial control of ground and rain water and the relief of pressure by unloading certain areas are feasible, and the Committee will confine its suggestions to these measures.

*Control of the Water.*—As early as the time of the first French Company the advantage of controlling the water was recognized; and the New French Company made several attempts to keep the water out of the relatively small slides of their time by surface drains and tunnels, but with only partial success. The Committee believes that every available and practicable device should be used to turn the water falling as rain from all ground that is sliding and prevent its entering adjacent ground, and it suggests the following measures:

1. *Covering Slopes with Vegetation.*—Whether vegetation increases or decreases the amount of rainfall entering the ground is still a moot question. The Committee believes, however, that threatening ground bordering the slides, quiescent slides, and, so far as practicable, active slides themselves, should be sufficiently covered with vegetation to prevent surface wash.

2. *Closing Peripheral Cracks.*—Before extensive movements of the

ground occur, warning is frequently given by the appearance of cracks peripheral to the coming slide. In some instances cracks exist for a long time before important movements take place. They are well illustrated upon Culebra Hill, west of the great break. As soon as they are formed they should be filled up, in order that they may not intercept surface water and lead it into the slide.

3. Drainage of Undisturbed and Threatened Areas.—Undisturbed and threatened areas near the slides should be thoroughly drained both by surface and by tile drainage, to keep as much water out of them as possible, for they may become unstable and they may supply water to the slides. The drainage water should be carried from the neighborhood of the slides as directly as practicable. Experiments with tile drainage on a small scale would soon show whether it is effective enough to justify its extension. The surfaces of the ground east of the East Culebra Slide and in places west of the West Culebra Slide, slope away from the adjoining slides, and the water can be readily removed. But a considerable area above the Cucaracha Slide drains naturally into it; some of the drainage can be diverted to the east, but the rest should, so far as possible, be collected by surface and tile drains, and be carried to the Canal through a large concrete-lined surface drain.

4. Drainage of the Great Slides.—A complete system of open drains should be established on the great slides and the water carried away as directly as possible. The main drains should be made impervious on the Cucaracha and, so far as practicable, on the two Culebra Slides.

5. Drainage by Tunnels.—Drainage by means of tunnels might be adapted to a few special cases, but should be tried with caution, and extended only in cases which promise results commensurate with the cost. The tunnels should be built underneath the sliding ground in the undisturbed material and strongly timbered so as to avoid risk of collapse, which would not only destroy the tunnel but would also disturb the overlying material. From the main tunnel smaller branches may be extended into the material to be drained and frequent borings made from the surface to conduct drainage water to the tunnels from the overlying strata. Such a system would be expensive, but might be effective in draining the area tapped by it.

*Relief of Pressure.*—It is suggested that a cut be made by sluicing in the East Culebra Slide, starting at an appropriate point on the Canal, and diverting from it diagonally in a general southeasterly direction, in the zone of gentle slopes and in such a position as to reach the large pond which now exists on the slide. This cut would partly separate the roughly rectangular slide into two approximately triangular parts, and

the adjoining ground could be sluiced along it into the Canal. It would provide a main drainage line for the ground on both sides of it, would empty the surface ponds and would lower the ground water in adjacent sliding material. The pressure of the triangle of ground in the rear of the cut against the triangle in front of it would be lessened; and it is probable that movement in the forward part of the slide would cease sooner than it would otherwise. When the cut is once established it offers a second line of defense against the slide by making it possible to work along two fronts.

A somewhat similar cut should be made in the West Culebra Slide. It should begin at the main drainage line opposite Culebra Hill and extend diagonally from the Canal in a general southerly direction, and should drain the existing pond.

#### STUDIES FOR THE FUTURE

In addition to the immediate remedial measures suggested above, there are certain observations and protective measures which should be undertaken with a view to the future.

*Detection of Movements of Earth or Rock.*—A few slides are now in motion, but many more are quiescent. A slide is not necessarily 'dead' because it has not moved notably for a few years. Its stability may hang on a delicate balance which may be disturbed by some slowly developing weakness. There is also a bare possibility that Gold and Contractors Hills are not so firmly supported as they are believed to be. Repeated surveys of properly placed signals for a number of years to come should be made in order:

(a) To indicate in good time where additional work of prevention is needed, to indicate how large a dredging fleet must be kept in readiness, and to furnish to the engineer of maintenance advance indications of emergency conditions.

(b) To test the effectiveness of remedial measures which may be taken to control or prevent slides. These tests would be more sensitive and definite than the mere occurrence or non-occurrence of slides.

(c) To furnish a reliable basis for confidence when, in the course of time, it appears that the earth and rock movements have so decreased that a condition of stability may be inferred.

*Core Borings.*—Definite information relative to the rock underlying Gold and Contractors Hills is wanting. Many years ago some borings were made at stations 500 feet apart along the center line of the Canal, some of them to a depth of 40 feet below sea level.

Two or three core borings should be made on each side of the Canal with a drill which would give large cores. At least one horizontal and one inclined hole should be bored on each side, their precise location to be fixed by a geologist.

*Underground Water and Related Data.*—As underground water is of paramount importance in promoting slides, it should be carefully studied in the Canal Zone. A satisfactory investigation of this problem would require the following determination and studies:

1. Profiles of water table for different localities of the Culebra District:
  - (a) In the wet and dry seasons;
  - (b) In areas in which remedial measures have been applied and similar areas where they have not.
2. Percentage of porosity of the several formations of the Culebra District:
  - (a) Absolute;
  - (b) With regard to size of grain.
3. The effect of tropical vegetation with the accompanying humus, its removal and its restoration, on:
  - (a) The amount of water which sinks underground in sliding and in undisturbed areas;
  - (b) Chemical action, such as oxidation, hydration, carbonation, etc.;
  - (c) The composition of the water;
  - (d) Changes in underground temperatures.
4. The nature of the changes which result in the disintegration and decomposition of the various rocks of the Culebra District when exposed to weathering agencies:
  - (a) With regard to volume;
  - (b) With regard to chemical changes, i.e., oxidation, hydration, carbonation, action of acids, etc.
5. The chemical changes which cause the so-called hot areas described by Colonel Gaillard and Mr. MacDonald:
  - (a) Direct, in production of acids, etc.;
  - (b) Indirect, i.e., the effect of produced acids upon the materials, including water and rock.
6. Observations to determine whether similar changes to those in the hot areas take place elsewhere to a less extent over large areas, and whether such changes affect the slides.

*Mechanical Testing of the Rocks.*—Sliding is largely dependent upon the strength of the rocks; which in turn is affected by the water content. The strength of the massive igneous rocks is well known to be great,

and need not be determined. But the Obispo, Cucaracha, and other formations of the Gaillard Cut should have their strength tested when saturated with water, when moist and when dry; and under rapid and slow deformation. If the tests show that much less force is required to deform the rocks when saturated or moist than when dry, this will emphasize the importance of keeping the water from these rocks so far as possible.

The tests should be made on fresh rocks and therefore in the Canal Zone. The specimens tested should be as large as is feasible for a testing machine of 200,000 pounds capacity.

*Earthquake Studies.*—There are now two seismographs installed in the Administration Building at Balboa Heights. It would be an advantage if the smaller instrument should be removed to a second station, for instance Colon, in order that the origin of earthquakes, occurring in regions within two or three hundred miles of the Canal Zone, may be more definitely determined. Some of the stronger shocks felt in the Zone have thrown the needles of the delicate seismographs off the paper and left the records incomplete. A low power instrument, magnifying about four times would secure a record of the movements of the ground in these cases.

#### GENERAL CONCLUSIONS

It is obvious that the sliding material which enters the Canal must be removed. The important thing for the future is to prevent ground from entering the Canal. The chief remedy proposed by the Committee to retard the movement of the slides now in motion and to prevent the slides from extending their areas, is to reduce the amount of water which goes underground. Methods have been suggested by which this can be done; and they should be vigorously applied to all moving and threatening areas.

The Committee looks to the future of the Canal with confidence. It is not unmindful of the labor necessary to deal with the present slides; and it realizes that slides may be a considerable, but not an unreasonably large, maintenance charge upon the Canal for a number of years; it also realizes that trouble in the Culebra District may possibly again close the Canal. Nevertheless, the Committee firmly believes that, after the present difficulties have been overcome, navigation through the Canal is not likely again to be seriously interrupted. There is absolutely no justification for the statement that traffic will be repeatedly interrupted during long periods for years to come. The Canal will serve the great purpose for which it was constructed, and the realization of that purpose in the near future is assured.